Chiral Magnetic Effect (CME) Overview

– 2024 RHIC/AGS annual users' meeting

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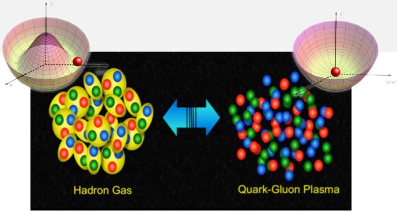
Outline

1. Introduction
2. Early experimental approaches
3. Recent experimental approaches
4. Summary and Outlook

Physics context



- QGP in heavy-ion collisions: quark mass negligible
  $\rightarrow$ **chiral symmetry restoration**
- **η-η' puzzle:** m_η(548 MeV) $< m_{\eta'}$(958 MeV) $\rightarrow$ not explainable with chiral symmetry. [Weinberg, *The U(1) problem*, PRD 11(1975)3583]
- **'t Hooft instanton mechanism** can resolve this puzzle
  ['t Hooft, PRL 37(1976)8], [Peccei, Lect. Notes Phys. 741(2008)3] $\rightarrow$ break the chiral symmetry, $\mathcal{P}$, and $\mathcal{CP}$.

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{\psi}_{q,a}\left(i\gamma^\mu\partial_\mu\delta_{ab} - m_q\delta_{ab} - g_s\gamma^\mu t^C_{ab}\mathcal{A}^C_\mu\right)\psi_{q,b} - \frac{1}{4}G^A_{\mu\nu}G^{A,\mu\nu} + \theta\frac{\alpha_s}{8\pi}G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}$$

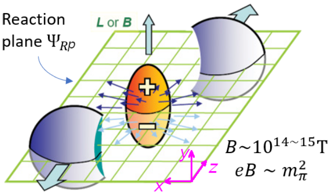
quark | quark-gluon interaction | gluon $\frac{1}{2}(E_A^2 - B_A^2)$ | 't Hooft vacuum $-\theta\frac{\alpha_s}{2\pi}\vec{E}_A\cdot\vec{B}_A$

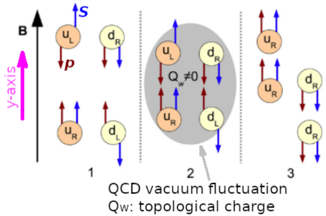
- low-energy experiments $\rightarrow$ θ upper limit $\sim 10^{-10}$
  [PDG, PTEP 083C01 (2022)], [Kim and Carosi, Rev.Mod.Phys.82(2010)557-602]
  $\rightarrow$ too small to explain the matter-antimatter asymmetry in the universe (**the strong $\mathcal{CP}$ problem**).

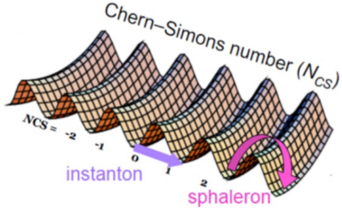
analogy to E&M field
$\vec{E}$: $\mathcal{C}$-odd, $\mathcal{P}$-odd, $\mathcal{T}$-even
$\vec{B}$: $\mathcal{C}$-odd, $\mathcal{P}$-even, $\mathcal{T}$-odd

- Is θ a constant? dependent on energy scale? larger value in early universe?
  Heavy-ion collisions approach the energy scale of early universe! $\rightarrow$ **check heavy-ion collisions!**

Chiral Magnetic Effect (CME)







[Kharzeev *et al.*, PRL 81(1998)512; NPA 803(2008)227]

QCD vacuum fluctuation → nonzero topological charge → imbalanced chirality

noncentral heavy-ion collisions → magnetic field $\vec{B}$ → opposite spins along $\vec{B}$ for $+/-$ charges

imbalanced chirality + opposite spins → opposite momenta along $\vec{B}$ for $+/-$ charges, charge separation, CME

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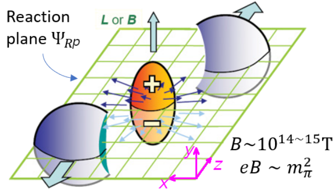
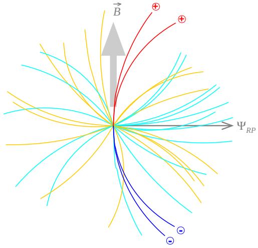
The commonly used observable–azimuthal correlator $\Delta\gamma$

azimuth Fourier series

$$\frac{dN^{\pm}}{d\phi^{\pm}} \propto 1 + 2a_1^{\pm}\sin(\phi^{\pm} - \Psi_{\rm RP}) + \sum_n 2v_n \cos n(\phi^{\pm} - \Psi_{\rm RP})$$



CME term $a_1^{\pm}$, in the same event $a_1 = a_1^{+} = -a_1^{-}$.
→ random direction from event to event → $\langle a_1 \rangle$ vanishes



two particles α, β in the same event

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \rangle,$$

Opposite-sign charged pair: $\gamma_{\rm OS}$; same-sign $\gamma_{\rm SS}$; their difference

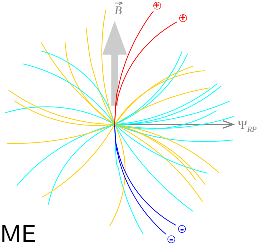
$$\Delta\gamma = \gamma_{\rm OS} - \gamma_{\rm SS}.$$

charge-independent backgrounds canceled (like momentum conservation)

[Voloshin, RPC 70(2004)057901]

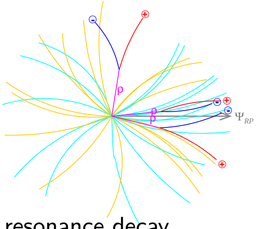
Signal and background in $\Delta\gamma$

signal

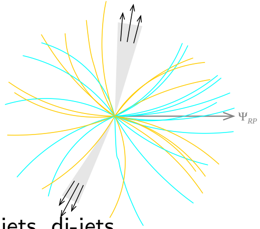


CME

backgrounds



resonance decay

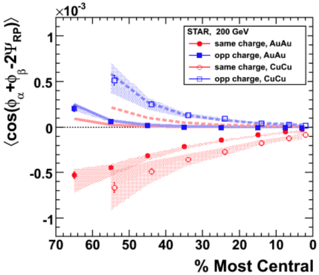


jets, di-jets

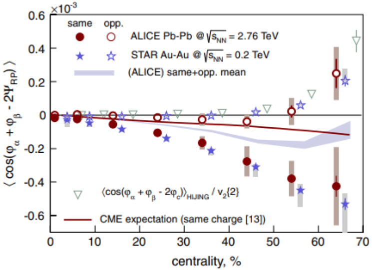
...

- 2-particle background like resonance decay (e.g., $\rho \to \pi^+\pi^-$), which is coupled with v_2.
  [Voloshin, RPC 70(2004)057901], [Wang, PRC 81(2010)064902], [Bzdak, Koch, Liao, PRC 81(2010)031901]
- In data analysis, RP is unknown, so the reconstructed event plane (EP) is used as a proxy.
  EP + 2 POIs $\to$ correlated triplets (jets, di-jets, ...) $\to$ background

The first measurements on $\Delta\gamma$



[STAR, PRL 103(2009)251601, PRC 81(2010)054908]



[ALICE, PRL 110(2013)012301]

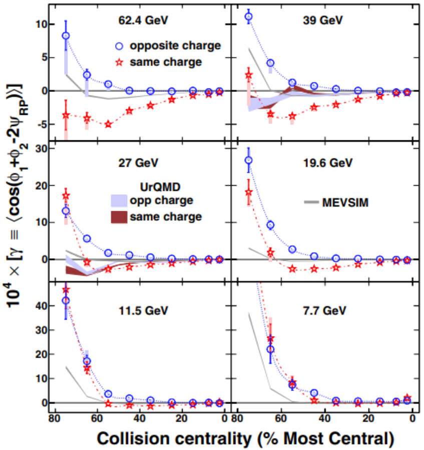
← similar results, though very different energy, species

- $\gamma_{\rm os} > 0, \gamma_{\rm ss} < 0 \rightarrow \Delta\gamma > 0$, qualitatively consistent with CME signal (?)
- background contribution not understood

  "Improved theoretical calculations of the expected signal and potential physics backgrounds ...are essential to understand whether or not the observed signal is due to [CME]." – [STAR, PRL 103(2009)251601]
- Follow-up calculations and simulations indicate that the backgrounds could be very significant

  [Wang, PRC 81(2010)064902] [Bzdak, Koch, Liao, PRC 81(2010)031901] [Schlichting, Pratt, PRC 83(2011)014913]

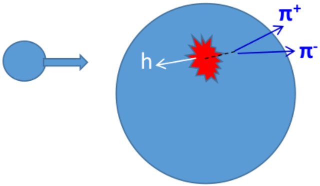
Beam energy dependence

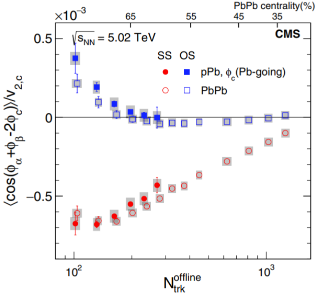


[STAR, PRL 113(2014)051302]

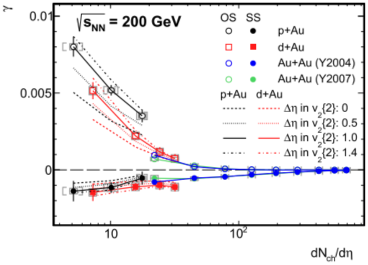
- STAR first beam energy scan (BES-I): Au+Au, $\sqrt{s_{\rm NN}} = 7.7 - 62.4$ GeV.
- *"weak energy dependence down to 19.6 GeV and then falls steeply at lower energies"* – [STAR, PRL 113(2014)051302]

Small system measurements





[CMS, PRL 118(2017)122301]



[STAR, PLB 798(2019)134975]

- Small system → random B and EP orientations → zero signal expected
- Similar results between small systems and A+A → large background

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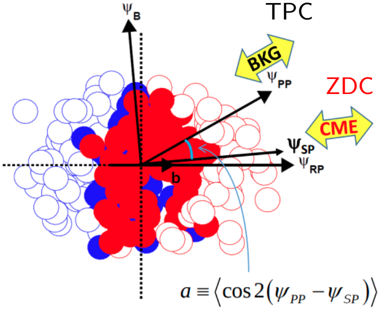
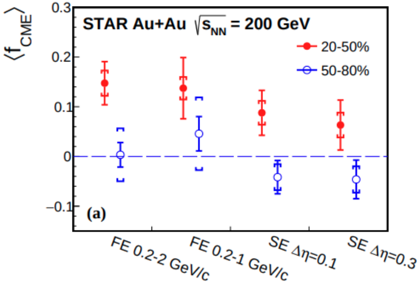
SP/PP comparison method



[H. Xu, *et al.*, CPC **42**(2018)084103]



[STAR, PRL 128(2022)092301]

$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

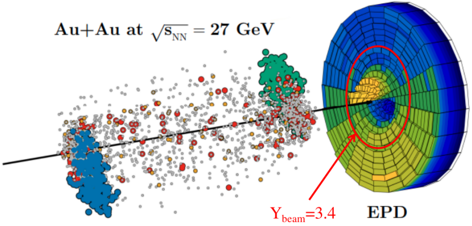
$$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\}$$

$$f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{EP}\}}{\Delta\gamma\{\mathrm{EP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

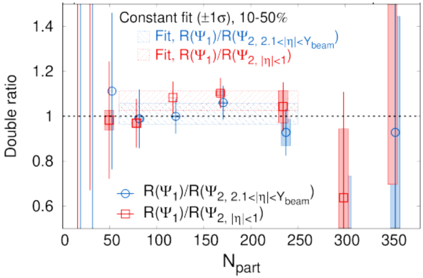
- Participant plane (PP) → nucleons collided → collision zone → flow → backgrounds w/ flow
- Spectator plane (SP) → nucleons flying through → magnetic field → CME signal
- The signal and background(coupled with flow) respond to those two planes differently → SP, PP comparison → separate the signal and background(coupled with flow)

residual background: nonflow

SP/PP comparison method



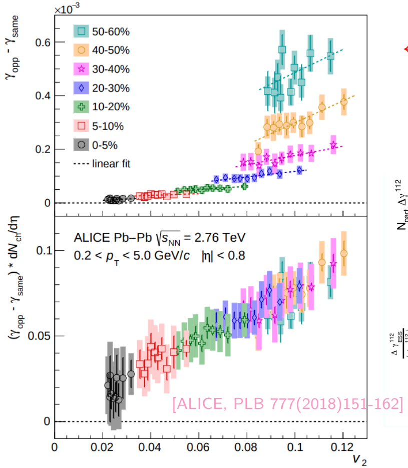
[STAR, PLB 839(2023)137779]



← consistent with unity

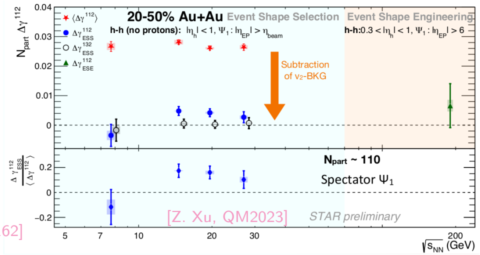
- Notation $R(\Psi) = \Delta\gamma(\Psi)/v_2(\Psi)$
- low energy 27 GeV → beam rapidity $Y_{\text{beam}} = 3.4$ → EPD $(2.1 < |\eta| < 5.1)$ divided into 2 parts
  - inner EPD $3.4 < |\eta| < 5.1$ → estimate SP
  - outer EPD $2.1 < |\eta| < 3.4$ → estimate PP (blue markers)
- TPC $(|\eta| < 1)$ is also used for PP (red markers)

Event shape methods



$\leftarrow$ Event Shape Engineering (ESE): observables, $q_2 \leftarrow$ different η ranges

$\downarrow$ Event Shape Selection (ESS): observables, $q_{2,\text{pair}} \leftarrow$ same η range



observables: $\Delta\gamma$, v_2
event shape variable:
ESE: (single particle)

$$q_2^2 = \frac{(\sum \cos 2\phi)^2 + (\sum \sin 2\phi)^2}{N}$$

ESS: (particle pair)

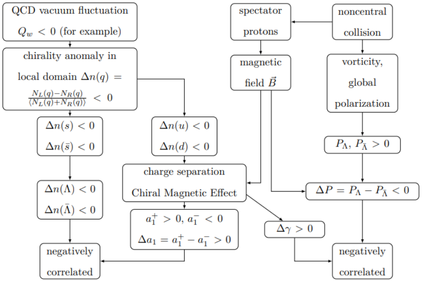
$$q_{2,\text{pair}}^2 = \frac{(\sum \cos 2\phi)^2 + (\sum \sin 2\phi)^2}{N(1+N\langle v_2\rangle)}$$

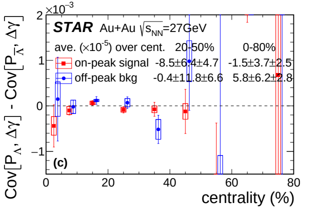
General idea:

- bin events by q_2 range
- calculate $\Delta\gamma$, v_2 for each bin
- map $\Delta\gamma$-v_2 $\to$ linear fit $\to$ intercept at $v_2 = 0$

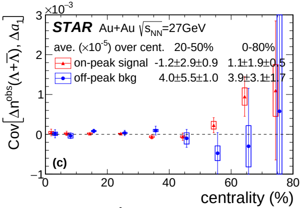
- STAR measurements w.r.t. SP (ZDC or inner EPD) can reduce nonflow backgrounds
- Event shape methods are designed to remove backgrounds coupled with flow.
- Underlying complications $\to$ better understanding needed

Correlation between CME observables with Λ measurements

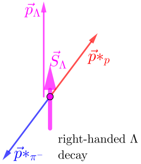


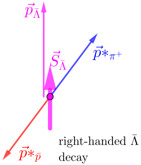


[STAR, PRC 108(2023)014909]



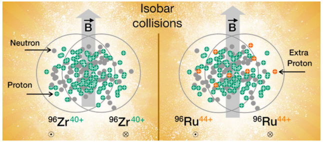
consistent with zero



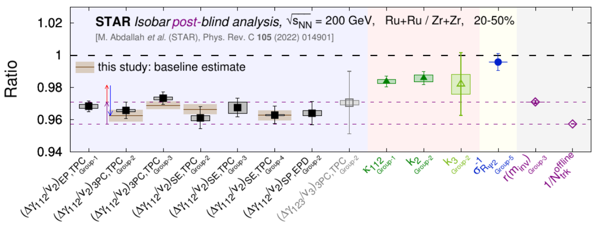


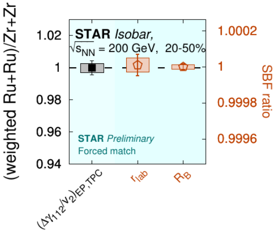
- magnetic field $\rightarrow \Lambda,\ \bar{\Lambda}$ polarization split $\rightarrow$ correlated with $\Delta\gamma$.
- topological charge fluctuation
  $\rightarrow$ CME sign (Δa_1) and Λ handedness $\rightarrow$ correlated
- The results are consistent with 0 within uncertainty.

The isobar experiment



- **initial expectation:** $^{96}_{44}$Ru, $^{96}_{40}$Zr: same A, different Z $\rightarrow$ same background, different signal
- Ru+Ru: proton number $\uparrow$ $\rightarrow$ magnetic field $\uparrow$ $\rightarrow$ CME signal $\uparrow$ $\rightarrow$ $\Delta\gamma/v_2 \uparrow$ $\rightarrow$ Ru/Zr > 1

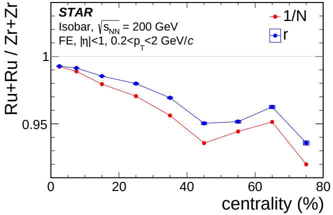




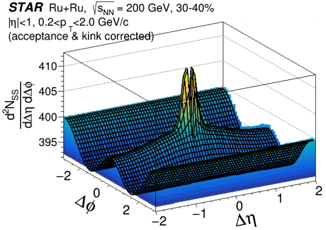
- **STAR blind analysis** [STAR, PRC 105(2022)014901] $\rightarrow$ isobar ratios Ru/Zr < 1, opposite to the initial expectation $\leftarrow$ multiplicity diff. $\leftarrow$ nuclear structure [Xu *et al.*, PRL121(2018)022301] .
- Nonflow background baseline estimate $\rightarrow$ CME upper limit 10% $(95\%$ CL) [STAR, arXiv:2308.16846, 2310.13096, QM2023] . Forced match method (N, v_2, EP res.) [STAR, QM2023] $\rightarrow$ consistent with unity

The isobar experiment

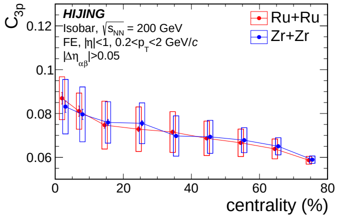
flow-induced backgrounds:
resonance decays → estimated by pair excess $r = \frac{N_{\rm OS} - N_{\rm SS}}{N_{\rm OS}}$

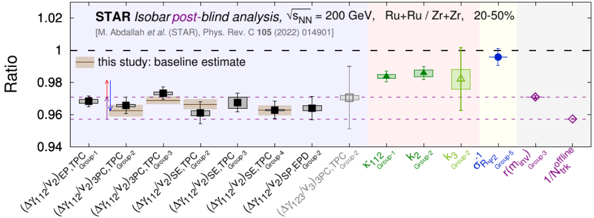


nonflow in v_2 measurement:
fit two-particle $(\Delta\eta, \Delta\phi)$ 2D distribution to decompose



3-particle nonflow:
HIJING model → no flow → solely 3p nonflow bkg



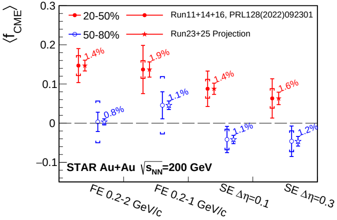


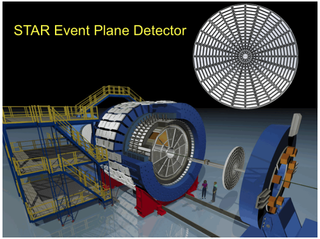
- **Post-blind:** nonflow background baseline estimate → CME upper limit 10% $(95\%$ CL)

[STAR, arXiv:2308.16846, 2310.13096] .

Outlook

year	minimum bias $[\times 10^9$ events$]$
2014 2016	2
2023 2025	20





- STAR: $\times 10$ more statistics for Au+Au at 200 GeV in 2023-2025

$\rightarrow$ large reduce in statistical uncertainty

- newly-added detectors can help (e.g, EPD, iTPC, ...)

[STAR, *Beam Use Request for Run23-25*, tab 5]

Summary

- CME – a fundamental physics in QCD
- Major background contamination
- Novel methods to extract CME
  - Isobar experiments
  - Event shape methods
  - Correlation measurement of CME–Λ polarization
  - SP/PP methods (TPC, ZDC, EPD)
- $\times 10$ more statistics, wider acceptance